

# INITIAL JUPITER ORBIT INSERTION AND PERIOD REDUCTION MANEUVER PLANS FOR JUNO

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This paper describes the initial plans for the New Frontiers Juno mission at Jupiter. It includes the considerable contingency planning for mission recovery if the Jupiter Orbit Insertion (JOI) burn to place Juno into a large capture orbit were interrupted or terminated on a burn timer setting, and the options for the mission if the Period Reduction Maneuver (PRM) burn to achieve the final orbit period were terminated early. The analyses were based on the assumption that 14-day orbits were the desired operational orbit period.

## INTRODUCTION

The Juno mission is a study of Jupiter's interior through a series of polar orbits at evenly spaced longitudes and with close perijove altitudes. At launch in August 2011, the mission plan for Jupiter included the Jupiter Orbit Insertion (JOI) burn on July 5, 2016, using the bi-propellant main engine into a single 107-day capture orbit, and then another main engine burn (PRM, the Period Reduction Maneuver) on October 19, 2016 to deliver 11-day orbits. The reference mission with 11-day period and 30 science orbits would provide 12° equal longitude spacing at equator crossings and just one extra orbit before deorbiting into Jupiter to ensure planetary protection for Europa.

Shortly after the Earth flyby in October 2013, a series of safing events led the project to consider a longer orbit period for the science mission. The project was concerned that a potential safing event at Jupiter might cause a several-orbit loss to science. More than one spacecraft anomaly over the course of the mission might be especially problematic for recovering missed longitudes. With the radiation dosage increasing with each perijove passage, and solar conjunction in October 2017, it was not necessarily clear that additional orbits could be added at the end of the mission to recover missed longitudes in the magnetic field map. The science mission and instruments are described in paper by Matousek<sup>1</sup>.

## STUDY OF TRAJECTORY ALTERNATIVES

The Juno Navigation Team undertook a two-part study 1) to identify capture orbit options to allow for more early science, and 2) to increase the orbit period for the science phase (following PRM) that would allow more time to respond to potential spacecraft anomalies. This paper describes work that resulted in the selection of the 53.5-day capture orbit and the 14-day science

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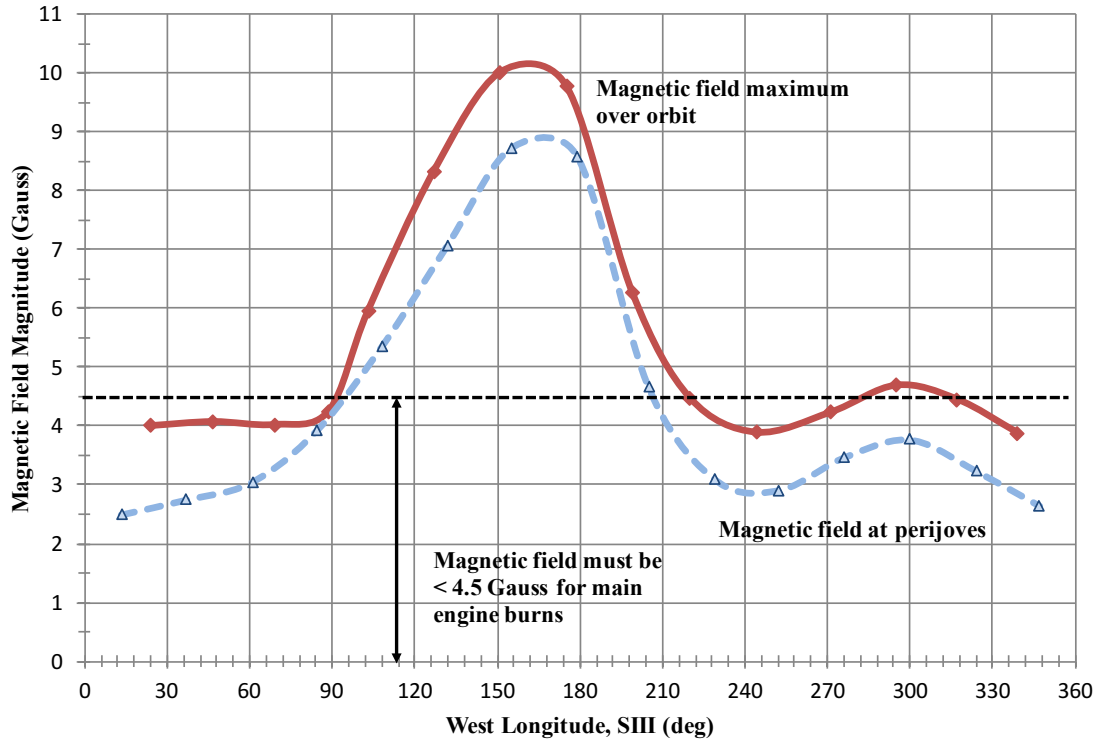
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orbit and the contingency analyses to identify options for recovery from potential anomalies of the main engine burn on the JOI or PRM events.

### Pre-PRM Characterization Orbits

For the JOI and PRM orbits, the instrument suite was expected to be inactive to avoid complicating these important main engine burns and to remove a potential safing event cause. Splitting the capture orbit into two or three orbits would allow for early science return but at the expense of more radiation for the extra orbit(s). The guidelines for evaluating these potential “characterization” orbits included: 1) burn duration less than 42 minutes (the value for which the main engine had been qualified through pre-launch testing) and 2) PRM date with low magnetic field ( $< 4.5$  Gauss) and centered near maximum elevation at the Goldstone DSN complex.



**Figure 1. Magnetic Field Magnitude at Perijove and Maximum over Orbit**

Figure 1 displays the expected magnetic field as a function of west longitude at perijove. Jupiter rotates at a rate of  $870.536^\circ/\text{day}$  so changing the PRM date by one day (where “one” day is actually 0.9975 days due to the Earth-Jupiter synodic period) means that the longitude at perijove changes by about  $148.4^\circ$ . The 0.9975 factor preserves the coverage over the Goldstone DSN complex as the nominal configuration on October 19, 2016 – the original PRM epoch. This same 0.9975 factor is also needed to maintain perijoves over Goldstone for the science orbits.

Table 1 displays the range of capture orbit options considered. Several potential options had to be discarded because the magnetic field magnitude would have been too high ( $> 4.5$  Gauss) to execute PRM on that date.

**Table 1. Capture Orbit Options**

Period (days)	Number of Orbits Before PRM	PRM Date	West Longitude at PRM Perijove (deg)	JOI Duration (min)	Pros/Cons
28	Direct to 28-day science orbits	None	N/A	45.6	Exceeds max. duration for main engine
33	3	10/11/16	246	42.1	Exceeds or too close to maximum duration for main engine burn; more radiation
35	3	10/17/16	56	41.1	
37	3	10/23/16	22	40.2	
39	3	10/29/16	36	39.4	2 orbits more radiation
43	3	11/10/16	16	38.0	
53.5	2	10/19/16	353	35.1	Retains original PRM date but extra perijove passage not over Goldstone
56	2	10/24/16	14	34.5	No real advantage over 53.5 day which retains original PRM date
107	1	10/19/16	353	28.4	No change

The project decided on the option with the 53.5-day orbit period and one additional perijove between the JOI and PRM events. This option retained the original October 19<sup>th</sup> PRM date, provided margin against maximum burn duration, and increased the radiation dosage only slightly.

### Science Orbit Period Options

The Juno project wanted an orbit period longer than 11 days in order to be able to respond to potential anomalies and not lose several orbits in the process. There were a variety of options considered, subject to the following key constraints:

- 1) Overall longitude spacing by end of mission of 12 degrees or better for the magnetic field investigation.
- 2) Longitude cadence that builds first a coarse map, then a finer map
- 3) Perijoves (PJs) over Goldstone complex with DSS-25 for Ka-band uplink/downlink for gravity science; ideally the view period between rise at 10° elevation and set at 15° elevation should contain the uplink for PJ-3hrs through PJ+3hrs.
- 4) Perijove altitude between 3100 km and 8000 km.
- 5) Inclination of 90°, +/- 10°

Most of the longitude spacing between subsequent equator crossings occurs naturally by the rotation of Jupiter and the orbit period. This “natural delta-west-longitude” is given by

$$\text{Natural } \Delta W.\text{Long.} = (870.536^\circ/\text{day} * 0.9975 * \text{integer-period days}) \text{ modulo } 360^\circ$$

To get a design value for the longitude between orbits, the  $\Delta W.\text{Long.}$  value is rounded off slightly so that, over a set of orbits, the longitude pattern would repeat if not modified. For example, for the 11-day baseline the natural delta-longitude value is 191.88° which is rounded to a design value of 192°. With 192° spacing between orbits, the entire 360° of Jupiter is mapped out in fifteen orbits with a spacing of 24°. Then a mid-mission shift of 12° is made and the process is repeated to bisect the existing longitudes that were covered in the first phase. At the end of 30 orbits, the

Jovian equator has been mapped to a 12° resolution. This longitude map is needed for the magnetic field investigation. One additional orbit was included to allow for recovery of a single missed longitude over the mission before deorbiting into Jupiter at end of mission. For the cases considered, sometimes several mid-mission shifts were required to achieve the desired longitude spacing.

Other factors to consider in the design and evaluation of alternate orbit periods are:

- 1) The maneuver  $\Delta V$  cost to achieve the desired longitudes and location in time of individual perijove data received at the Goldstone complex. Generally, more  $\Delta V$  is required to achieve the desired longitude if there is a large difference between the “natural”  $\Delta$ longitude and the design  $\Delta$ longitude.
- 2) Longitude cadence which provides an early coarse mapping and progresses to finer mappings was considered favorable.
- 3) Longer missions due to larger orbits and sometimes more orbits to achieve the final longitude spacing mean that there will be at least one solar conjunction occurring during the science mission (October 2017).
- 4) For longer missions, the data-intensive science perijove period from PJ-3hrs through PJ+3hrs cannot be wholly contained within a shrinking Goldstone view period near end of mission.
- 5) The orbit periods for 14 days, 21 days, and 28 days received special attention since they would synchronize with the 7-day human-centric work week.
- 6) Overall mission cost and length, including reliability of spacecraft components and radiation dosage for additional orbits.

Table 2 below illustrates the variety of orbit periods considered. There are many more options than those shown in the table, although not all cases were investigated extensively. The cases of most interest were the ones for 14-day, 20-day, 21-day, 22-day and 28-day orbit periods.

**Table 2. Options for Alternate Science Orbit Period**

Integer Orbit Period (days)	“Natural” Longitude Value between Orbits (deg)	Design Value for Longitude between Orbits (deg)	Difference between Design and Natural Values (deg)	# of Orbits for Repeat	# Long. Shifts	# Orbits for Coarse and Finer Resolution	Final Longitude Spacing (deg)
11	191.96	192.00	+0.04	15	1	15, 30	12.00
14	277.04	275.29	-1.75	17	1	17, 34	10.59
14	277.04	270.00	-7.04	4	7	4, 8, 16, 32	11.25
15	65.40	67.50	+2.10	16	2	16, 32	11.25
16	213.76	216.00	+2.24	5	5	5, 15, 30	12.00
20	87.19	90.00	-2.81	4	7	4, 8, 16, 32	11.25
21	235.55	240.00	+4.45	3	9	3, 15, 30	12.00
22	23.91	24.00	+0.09	15	1	15, 30	12.00
27	45.71	45.00	+0.71	8	3	8, 16, 32	11.25
28	194.07	192.00	-2.07	15	1	15, 30	12.00

The 22-day case was somewhat similar to the 11-day case with one mid-mission shift after 15 orbits, but the longitude difference between successive orbits was 24° so that the 15 orbits needed to map the entire 360° space occurred sequentially in one direction. The 11-day case had 192°

between successive orbits so that opposite areas of Jupiter were covered earlier. The 22-day case provided a poorer early coarse mapping of Jupiter.

The 14-, 21-, and 28-day cases were of special interest because they synched up well with a human 7-day work week. A distinctive feature of each of these was that the perijoves and maneuvers would always be on nearly the same day of the week (initially Wednesday). This feature potentially reduced workloads on weekends. The perijove day-of-week gradually moves one day earlier by the end of mission earlier for the 14-day case, and two days earlier for the 21-day and 28-day cases. This movement to an earlier day-of-week is due to the 0.9975 multiplicative factor in the orbit period for all cases.

At first, the particular 14-day case under consideration had 17 orbits for the initial longitude repeat and an unfavorable difference of 275.29° between successive equator crossing longitudes. In May 2014, the case of an alternative 14-day architecture with 270° between orbits was proposed and became a favorite with the science team. This case had the advantage that a coarse map was completed after only 4 science orbits, with subsequently finer maps after 8 orbits, 16 orbits, and 32 orbits. If the spacecraft should fail early, there could be an even distribution of longitudes completed much earlier than for most other alternate orbits being considered. This longitude cadence required significant shifts after each set of 4 orbits, but the  $\Delta V$  required for the shifts was deemed to be manageable.

The 20-day case had 90° shifts and similar longitude cadence, but the science assessment showed an undesirable geometry due to inertial rotation of the orbit at Jupiter beyond one year of operations.

### Selection of New Reference Mission

Ultimately, the 14-day science mission was adopted along with the 53.5-day capture orbit phase. The new reference was approved by NASA headquarters and released by the Juno project in March 2015. Table 3 shows the details of the reference mission.

**Table 3. 14-day Reference Mission Before JOI**

Orbit #	Perijove (PJ) Date	Orbit Purpose	PJ Altitude over Oblate Jupiter (km)	Equator Crossing West Longitude (deg)	Longitude Shift (deg)	Deterministic $\Delta V$ (m/s)
0	7/5/16 2:47	JOI	4489	33.34		541.7
1	8/27/16 12:51	Early Science	4147	97.00		1.5
2	10/19/16 18:11	PRM	4181	348.90		395.2
3	11/2/16 17:52	PRM Cleanup	4194	285.40		0.0
4	11/16/16 16:54	MWR	4233	198.25		1.7
5	11/30/16 15:52	Gravity	4324	108.25		0.0
6	12/14/16 14:49	MWR	4357	18.25		2.4
7	12/28/16 13:47	MWR	4375	288.25		1.0
8	1/11/17 13:59	Gravity	4418	243.25	45	7.9
9	1/25/17 12:57	MWR	4394	153.25		2.9
10	2/8/17 11:54	Gravity	4377	63.25		1.8
11	2/22/17 10:52	Gravity	4313	333.25		2.0
12	3/8/17 9:12	Gravity	4285	220.75	-22.5	3.8
13	3/22/17 8:10	Gravity	4358	130.75		1.4
14	4/5/17 7:07	MWR	4491	40.75		0.0
15	4/19/17 6:05	Gravity	4598	310.75		4.2

16	5/3/17 6:17	Gravity	4742	265.75	45	4.3
17	5/17/17 5:14	Gravity	4853	175.75		0.1
18	5/31/17 4:12	Gravity	4926	85.75		1.3
19	6/14/17 3:10	Gravity	5005	355.75		6.4
20	6/28/17 3:40	Gravity	5145	322.00	56.25	3.8
21	7/12/17 2:38	Gravity	5251	232.00		3.1
22	7/26/17 1:35	Gravity	5338	142.00		2.4
23	8/9/17 0:35	Gravity	5431	52.00		3.8
24	8/23/17 0:08	Gravity	5495	344.50	22.5	2.7
25	9/5/17 23:05	Gravity	5526	254.50		2.5
26	9/19/17 22:03	Gravity	5628	164.50		3.7
27	10/3/17 21:00	Gravity	5785	74.50		0.5
28	10/17/17 20:35	Gravity	5933	7.00	22.5	2.9
29	10/31/17 19:33	Gravity	6105	277.00		0.4
30	11/14/17 18:30	Gravity	6288	187.00		0.1
31	11/28/17 17:28	Gravity	6519	97.00		1.8
32	12/12/17 17:02	Gravity	7095	29.50	22.5	2.0
33	12/26/17 16:00	Gravity	7417	299.50		2.0
34	1/9/18 14:57	Gravity	7622	209.50		0.4
35	1/23/18 13:55	Gravity	7812	119.50		0.7
36	2/6/18 12:52	Extra Orbit, Deorbit	7950	29.50		77.0
37	2/20/18 11:39	Impact	-700	291.56		

With the longitude targets in Table 3 and the shifts after each four orbits, the overall longitude mapping advances from coarse to finer in the following stages:

- 1) 90° spacing: Orbits 4 through 7
- 2) 45° spacing: Orbits 4 through 11
- 3) 22.5° spacing: Orbits 4 through 19
- 4) 11.25° spacing: Orbits 4 through 35

Maneuvers for orbits dedicated to the MWR (microwave radiometer) instrument have Orbit Trim Maneuvers (OTMs) at 7.5 hrs after perijove. The MWR instrument provides measurements at various depths to help characterize Jupiter's interior. The early perijoves are dedicated to MWR measurements because the instrument was only expected to survive about 10 orbits due to radiation exposure. Maneuvers for gravity science have most of the maneuvers placed at perijove+6hrs, with a handful orbits (8, 12, 15, 16, 19, 20, and 26) at perijove+4hrs to reduce the size of the maneuver. The PJ2 altitude was lowered to ensure that perijove altitudes remained under 8000 km in the mission. Inclination was under 91° for the entire mission and required no special control.

As a spin-stabilized spacecraft, most maneuvers (except main engine maneuvers) are performed in vector mode with the spacecraft high gain antenna oriented toward Earth. The lateral thrusters are utilized far more than the axial thrusters in the orbital mission, so for conservatism, the estimate for propellant (hydrazine) usage was largely based on finite burn formulation of the lateral thrusters for maneuvers.

Total deterministic  $\Delta V$  for the OTMs in Table 3 described above is approximately 76 m/s which is nearly double the cost for 11-day orbits, but well within the available propellant. Mean  $\Delta V$  for the OTMs is about 81 m/s with  $\Delta V_{99}$  about 106 m/s. These values exclude the deorbit maneuver. The available hydrazine and corresponding  $\Delta V$  (some of which is available for recovery from JOI

and/or PRM contingencies) is about: 183 kg (~200 m/s) in a deterministic sense, about 174 kg (~190 m/s) for the mean, and about 160 kg (~175 m/s) for  $\Delta V_{99}$ .

## **STRATEGIES FOR RECOVERING MISSION IN EVENT OF BURN ANOMALY**

The strategy for recovery from an anomaly at JOI or PRM was to adjust the maneuver design and timing to preserve the baseline mission plan (October 19 PRM date, 14-day orbits) whenever possible, or adjust maneuver design and timing to return to the baseline plan at later time (later PRM epoch and 14-day orbits). For more severe contingencies, the mission might need to be completely redesigned to meet Juno science objectives.

## **CONTINGENCY STUDIES FOR JOI MANEUVER**

JOI is obviously a critical maneuver, since without it there can be no orbital mission. The nominal JOI burn sequence included about a 90° turn from Earth point to the JOI attitude, spin up from 2 to 5 rpm, hold times, burn duration of about 35 minutes, spin down to 2 rpm, and turn back to the sun/Earth direction. The burn itself was timed to occur (and be observed via “tones” through the toroidal antenna) during the 4-hr overlapping view period at Goldstone and Canberra. An auto-restart capability was enabled for JOI, i.e., if the main engine stopped burning, it would attempt a restart (after a 500-sec wait period) to enable burn completion. Most other fault responses were disabled. Subsequent sections of this paper describe recovery from anomalies relating to interruption of the JOI burn or due to timer cutoff.

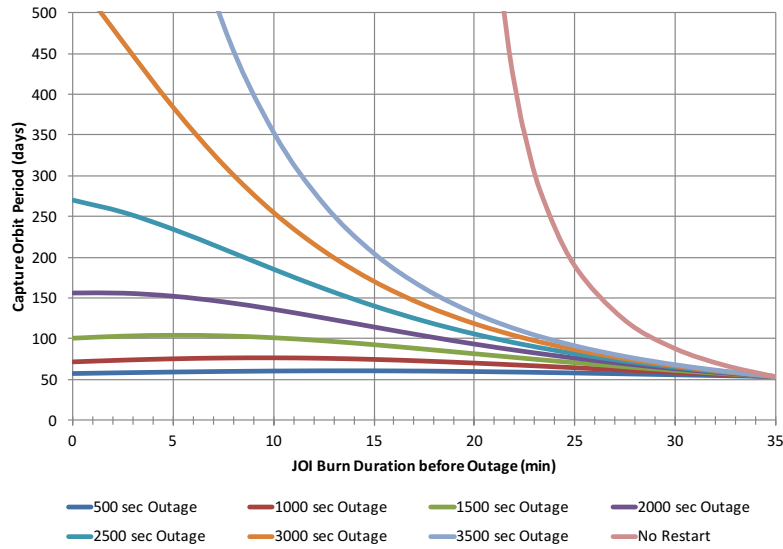
For all JOI contingency cases, the ground rules for recovery included finding another suitable epoch to perform a redesigned PRM maneuver (low magnetic field magnitude and burn over Goldstone complex) and with a burn duration to give 14-day science orbits. The “recovery” trajectories usually extended only to the perijove with the first targeted longitude of the four-orbit set, with additional maneuvers permitted at the JOI cleanup location (about 8 days after JOI) and following the first science perijove (usually at PJ1+6hrs). The hydrazine cost computation for these maneuvers utilized finite lateral burn formulation (since most maneuvers were in lateral instead of axial direction for the spinning spacecraft). Overall delta-V and hydrazine used was tracked and compared to the nominal case. About 25 kg was the approximate limit allowed for recovery without changing to a later PRM epoch. Although there was about 150-200 kg of hydrazine available, much of that was reserved for the orbital mission itself.

The studies utilized both CATO (Computer Algorithm for Trajectory Optimization), a medium-high fidelity software program, and COSMIC, a trajectory optimization application delivered as part of the MONTE<sup>2</sup> software suite for mission design and navigation at the Jet Propulsion Laboratory.

The contingency cases considered for JOI included delayed start, interrupted JOI burn, early termination, faulted attitude, and burn terminated by cutoff timer prior to reaching the planned delta-V. The interrupted burn and timer cutoff scenarios are detailed in this paper.

### **Interrupted JOI Burn**

The JOI burn was centered around perijove, so that a delayed start or an interrupted burn would result in much of the burn occurring at a less optimal time. Even if JOI were able to restart and complete the total maneuver duration, the overall result would be a less efficient JOI maneuver and a larger than desired capture orbit.

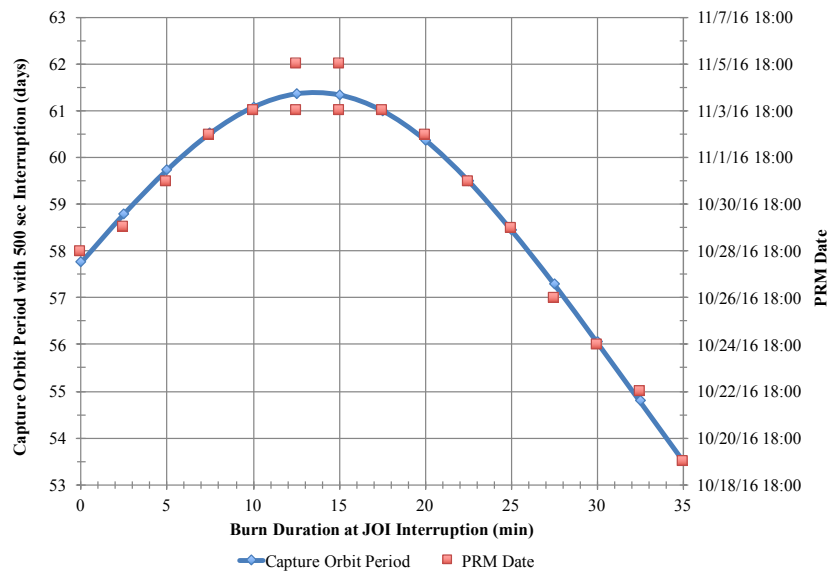


**Figure 2: Capture Orbit Period versus JOI Burn Duration for Various Outage Durations**

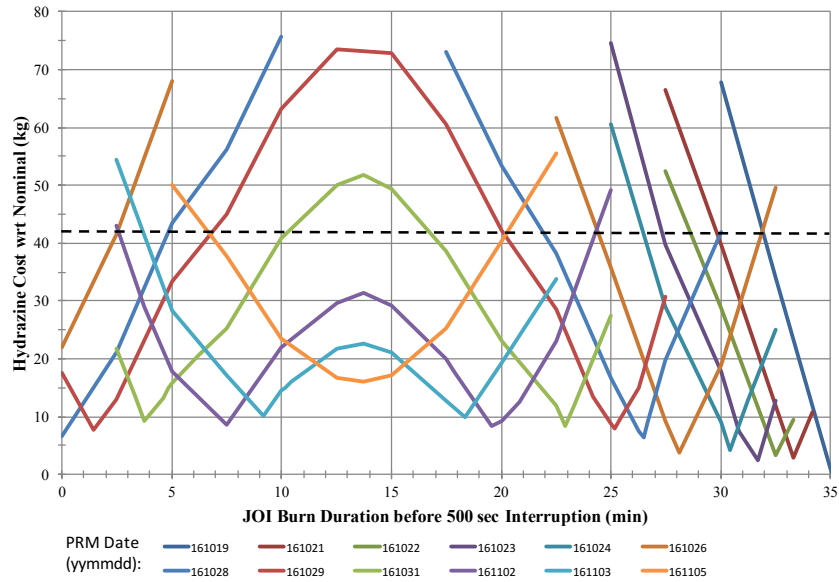
Figure 2 shows the resulting orbit period if the JOI burn were interrupted after various durations but still completed the nominal duration after one or more restart events. The main engine needs to burn at least 22.5 minutes without interruption in order for the spacecraft to be captured into an approximate one-year orbit, and about 25 minutes to achieve a six-month orbit.

#### Single 500-sec Interruption of JOI Burn

The case of a single 500-sec interruption was studied in detail. Depending on when the outage occurs, the resulting capture orbit period can be up to 8 days longer than nominal (Figure 3), so the new optimal PRM date could be 15 or 17 days after October 19th. (November 4<sup>th</sup>, which is 16 days after October 19th, has a high magnetic field magnitude and cannot be used for recovery.)

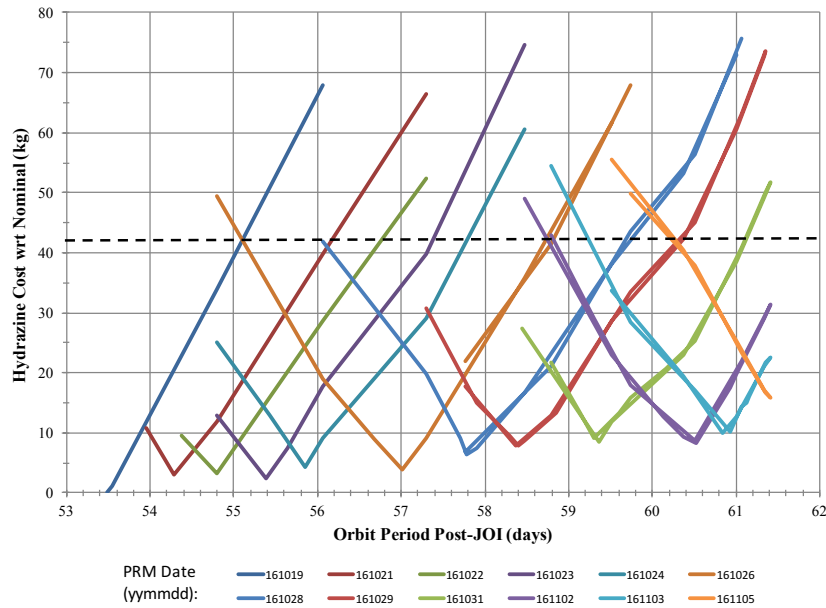


**Figure 3. Capture Orbit Period and PRM Date after 500-sec Interruption**



**Figure 4. Hydrazine Cost to Recover from 500-sec Interruption of JOI Burn as Function of Burn Duration before Outage (with Varying PRM Dates)**

Figure 4 displays the extra hydrazine required to recover from a single 500-second outage during the JOI burn. The nominal October 19<sup>th</sup> PRM date can be retained at a cost of 25 m/s only if the burn interruption occurs more than 33 minutes into the 35-minute burn. Otherwise, PRM and the 14-day mission must be moved to a later date. Figure 5 displays the same information but as a function of capture orbit period rather than burn duration before interruption.



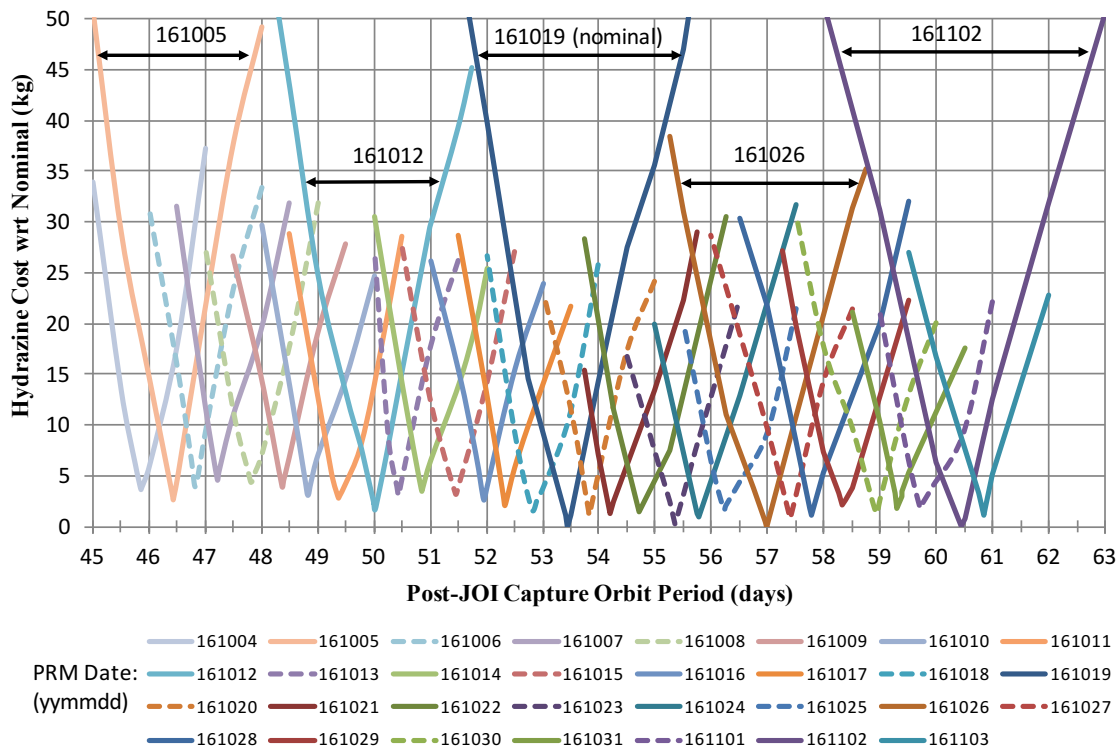
**Figure 5. Hydrazine Cost to Recover from 500-sec Interrupted JOI Burn as Function of Capture Orbit Period (with Varying PRM Dates)**

For recovery from a 500-sec interrupted burn, the hydrazine cost is 10-20 kg; however, it is possible to retain 14-day science orbits with Wednesday perijoves, at a hydrazine cost of about 42 kg. From Figure 4, using the intersections of the cost curves for 161026, 161102 and 161019 near the dashed 42 kg line, the optimal approach would be to select:

- 1) October 26<sup>th</sup> PRM date (+7 days) for interruptions at 0 thru 2.5 min
- 2) November 2<sup>nd</sup> PRM date (+14 days) for interruptions at 2.5 min thru 24 min
- 3) October 26<sup>th</sup> PRM date (+7 days) for interruptions from 24 min to 32 min
- 4) October 19<sup>th</sup> PRM date (+0 days) for interruptions from 32 min to 35 min

### JOI Timer Settings

Juno's main engine performed very well at the two Deep Space Maneuvers in late summer 2012 with the actual and predicted burn durations matching to within seconds. The JOI burn was likewise expected to provide a very precise burn, but burn timers were still set to provide a minimum and maximum range of burn durations in the event that the inertial measurement unit (IMU) failed. A value about 1% would have encompassed the maximum variation for both burn performance and IMU performance, but the timers for JOI were purposely set at very large limits, -4.07% to +5.18%. These limits were chosen so that the capture orbit period would have been 7 days smaller (for a burn terminated at timer maximum) or 7 days larger (for a burn terminating at timer minimum). The PRM dates would be 14 days earlier or 14 days later, (October 5<sup>th</sup> or November 2<sup>nd</sup>), respectively. Thus, in a "worst case" JOI performance scenario, much of the pre-JOI science planning would be preserved.



**Figure 6. Hydrazine Cost for Recovery to 14-day Mission as Function of Capture Orbit Period and PRM Date**

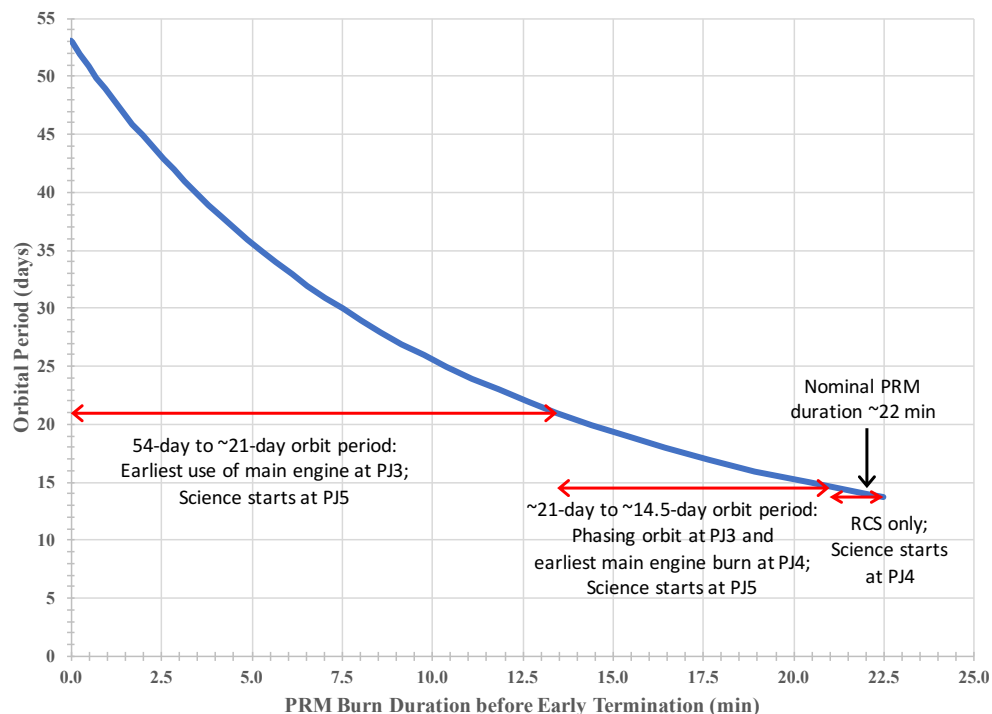
Figure 6 shows the hydrazine cost to recover from an anomalous JOI burn based on the post-JOI orbit period. Finite lateral maneuver formulation for JOI cleanup at JOI+8.6 days and at PJ1+6 hours was used. The dashed lines represent those PRM dates for which the magnetic field magnitude is too large to perform a PRM main engine burn. This plot is useful to assess hydrazine cost for a wide variety of JOI contingencies. The cost for recovering a 14-day mission is less than 20 kg and often only 10 kg.

## CONTINGENCY STUDIES FOR PRM

Contingencies associated with the Period Reduction Maneuver, or PRM, are also considered. PRM is needed to reduce from the orbit period from the capture orbit phase to the desired science orbit period. PRM had no restart capability enabled for the main engine burn. Unlike JOI, PRM was not considered to be a “critical” maneuver because another main engine burn could be attempted on a subsequent perijove in the event of a PRM anomaly. The Juno spacecraft configuration included an extra “pyro” event for a fifth main engine burn.

The nominal PRM burn at perijove 2 (PJ2) had a duration of about 22 minutes and like JOI was performed in a direction nearly normal to the Earth line. PRM was centered in the Goldstone complex view period and included an arraying of four 34m antennas in addition to the 70m antenna. This timing was needed in order to synch up the perijoves for the science orbits over Goldstone. The burn timers were set to be about  $\pm 2\%$ .

If the PRM burn terminated early, there was a possibility of using the main engine again on another perijove if the orbit period was not close to the desired 14-day orbit and if the project felt that any adverse risk of use was minimal.



**Figure 7. Options for Use of Main Engine in Event of Early Termination of PRM**

Figure 7 shows the option space for use of the main engine which is dependent on the orbit achieved after a partial-PRM burn.

- 1) For an orbit period greater than 21 days, the main engine burn could be scheduled for the next perijove, PJ3 (provided the low magnetic field magnitude condition is met). 21 days was considered to be the minimum time needed for planning another main engine burn. The science phase would then start at PJ5, one orbit later than the baseline. The orbit between the main engine burn and start of science (PJ4) was needed to clean up the main engine maneuver, similar to the function of orbit 3 in the reference mission.
- 2) For an orbit period between 14.5 and 21 days, the next orbit, PJ3, would be a phasing orbit, and the main engine burn would occur at perijove 4. Science would start two orbits later, at PJ6.
- 3) If the orbit period was 14.5 days or less, the main engine would not be needed. RCS thrusters would be used to trim the orbit period at PJ3, and science would start at PJ4.

The hydrazine cost associated with any of the above three scenarios is under 20 kg.

For the case of a partial PRM burn with no additional main engine burn possible, a complete redesign of new reference mission may be required to achieve the Juno science mission objectives. This process would be similar to that which resulted in the selection of the 14-day orbits. There are many options to get equally spaced longitudes over the range of possible post-PRM periods; however, only a relatively small change in orbit period might be achievable and require several sizeable maneuvers to transition to another orbit period, since the RCS thrusters are much less efficient than the main engine. Because of continued radiation exposure during the transition orbits and then the mapping orbits, an orbit mapping cadence from coarse to finer resolution would also become important.

## CONCLUDING REMARKS

The Juno project redesigned its capture orbit to provide an opportunity for early science at Jupiter and to test out the science instruments. The science orbit was redesigned from 11 days to a 14-day period to provide slightly longer time to react and recover from potential anomalies during the orbital phase and to provide an early coarse longitude mapping grid and then finer grids for the magnetic field investigation.

The Juno project was well prepared to handle a variety of contingencies for the JOI and PRM main engine burns. The JOI burn was executed flawlessly and the orbit 1 science perijove provided valuable early science. The PRM burn was called off about a week before its scheduled execution because of an issue with the main engine propulsion system, and the project has decided not to utilize the main engine again and instead remain in the current 53-day orbit. The trajectory design trade study for this revised mission is described in Pavlak, Johannesen, and Bordi.<sup>3</sup>

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